Phosphorus Losses in Furrow Irrigation Runoff

D. T. Westermann,* D. L. Bjorneberg, J. K. Aase, and C. W. Robbins

ABSTRACT

Phosphorus (P) often limits the eutrophication of streams, rivers, and lakes receiving surface runoff. We evaluated the relationships among selected soil P availability indices and runoff P fractions where manure, whey, or commercial fertilizer applications had previously established a range of soil P availabilities on a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) surface-irrigated with Snake River water. Water-soluble P, Olsen P (inorganic and organic P), and iron-oxide impregnated paper–extractable P (FeO-P_s) were determined on a 0.03-m soil sample taken from the bottom of each furrow before each irrigation in fall 1998 and spring 1999. Dissolved reactive phosphorus (DRP) in a 0.45-μm filtered runoff sample, and iron-oxide impregnated paper–extractable P (FeO-P_w), total P, and sediment in an unfiltered runoff sample were determined at selected intervals during a 4-h irrigation on 18.3-m field plots. The 1998 and 1999 data sets were combined because there were no significant differences. Flow-weighted average runoff DRP and FeO-P_w concentrations increased linearly as all three soil P test concentrations increased. The average runoff total P concentration was not related to any soil P test but was linearly related to sediment concentration. Stepwise regression selected the independent variables of sediment, soil lime concentration, and soil organic P extracted by the Olsen method as related to average runoff total P concentration. The average runoff total P concentration was 1.08 mg L^{-1} at a soil Olsen P concentration of 10 mg kg^{-1}. Soil erosion control will be necessary to reduce P losses in surface irrigation runoff.

There is increasing concern that P (phosphorus) losses from agricultural land cause accelerated algae and aquatic plant growth in lakes, rivers, and streams (Sharpley et al., 1999). Total P losses from agricultural fields are generally not large; however, concentrations that cause eutrophication can be as low as 0.02 mg P L^{-1} (USEPA, 1996). To control eutrophication, the USEPA (1986) recommended a limit of 0.05 mg L^{-1} for total P in streams that enter lakes and 0.1 mg L^{-1} for total P in flowing waters. Since these concentrations are substantially lower than the 0.2 to 0.3 mg L^{-1} inorganic P required in the soil solution for normal plant growth (Barber, 1995), it is essential that soil P availabilities and irrigation practices are managed to reduce the potential for P movement.

Surface irrigation runoff is known to carry both soil particles and P (Carter et al., 1974). Soil erosion only occurs in the furrows where the water is placed with surface irrigation. Also, because of infiltration, the erosive power of this stream becomes smaller as the stream moves downslope. Sediment losses from near zero to more than 100 Mg ha^{-1} have been reported for surface-irrigated crops (Carter, 1990). Efforts continue to develop acceptable management practices to control soil erosion since it seriously affects crop production (Carter et al., 1985).

Sediment eroded from irrigated agricultural soils typically contains 900 to 1200 mg kg^{-1} of total P. Clay particles may contain more than 1400 mg kg^{-1} total P while total P in sand can be as low as 450 mg kg^{-1} (Carter et al., 1974). The median seasonal total P lost from 32 surface-irrigated agricultural fields was 4.9 kg ha^{-1} and depended on the amount of sediment eroded (Berg and Carter, 1980). The median soluble P lost from the same fields was 0.15 kg ha^{-1}, or only 3% of the total P lost. Typically, the eroded sediment also contains more smaller-sized soil particles than in the non-eroded soil, causing nutrient enrichment in the runoff.

There is a great deal of effort underway to develop P management practices for agricultural land that will minimize the potential for P losses to affect offsite water bodies (Haygarth, 1997; Sharpley et al., 1999, 2000; Tunney et al., 1997). A necessary component of P management is knowing the relationship between soil P availability and P runoff loss since it could affect allowable P loadings from fertilizers, animal manure, or by-products. Agronomic soil P tests are available for crop production but their applicability for estimating P concentrations and losses in surface runoff is uncertain. Phosphorus concentrations in simulated rainfall runoff were better related to soil P extracted by distilled water, iron-oxide impregnated paper, and acidified ammonium oxalate than to the more common agronomic soil P tests on acid soils planted to fescue, *Festuca arundinacea* Schreb. (Pote et al., 1996). Later studies showed that the soil test P concentrations could be used to predict P losses in rainfall runoff across different soils when site hydrology was considered (Pote et al., 1999). Published studies that relate surface irrigation runoff P concentration with estimates of soil P availability are unknown.

Suspended sediment can act as a source of soluble P or it can act as a sink in aqueous systems. Little is known about the P dissolution–precipitation and sorption–desorption dynamics taking place in furrow irrigation water as it moves across a field. Diffusion of soluble P from the soil in the zone of runoff interaction is also thought to contribute to P losses (Logan, 1982). Research is currently underway to identify the physical and chemical processes that determine the timing and magnitude of P losses in runoff from surface- and sprin-

Abbreviations: DRP, dissolved molybdate-reactive phosphorus in filtered (0.45 μm) runoff water; FeO-P_s, iron-oxide impregnated paper–extractable phosphorus from furrow soil; FeO-P_w, iron-oxide impregnated paper–extractable phosphorus from unfiltered runoff water; Fur-P_i, bicarbonate-extractable inorganic phosphorus from furrow soil; Fur-P_o, bicarbonate-extractable organic phosphorus from furrow soil; Olsen P, bicarbonate-extractable soil phosphorus; PSI, phosphorus sorption index; total P, phosphorus concentration in unfiltered runoff water after persulfate digestion; water P, water-extractable inorganic phosphorus from furrow soil.

USDA-ARS, Northwest Irrigation and Soils Research Lab., 3793N 3600E, Kimberly, ID 83341. Received 5 July 2000. *Corresponding author (dtw@kimberly.ars.pn.usbr.gov).

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kler-irrigated soils. The objective of this study is to determine the relationships among selected methods of soil P availability and the P in surface irrigation runoff from a calcareous silt loam soil.

MATERIALS AND METHODS

Soil P–runoff P relationships were evaluated where different rates of manure, whey, and commercial fertilizers were previously applied to 16 field plots (Robbins et al., 1997) on Portneuf silt loam. Eight topsoil plots were relatively undisturbed, while the upper soil layer (0.3 m) was removed on the eight subsoil plots in 1991 to expose the calcic layer. The selected treatments produced a wide range of initial soil test P concentrations and availabilities (Table 1). Average field slope was 1%.

The irrigation water source was the Snake River (pH = 8.2, electrical conductivity = 0.5 dS m^{-1}, sodium adsorption ratio = 0.7, total P < 0.10 mg L^{-1}, and DRP < 0.01 mg L^{-1}). Water was applied in September 1998 and May 1999 at 28 L min^{-1} in small, wheel-track furrows spaced 0.76 and 1.12 m apart, respectively. Inflow rates were chosen to simulate erosion conditions found at the upper end of an irrigated field. Furrows were formed a few days before each irrigation. The same plots were used for both the 1998 and 1999 irrigations. The 1998 irrigation followed dry bean (*Phaseolus vulgaris* L.) and the May 1999 irrigation was soon after planting of spring wheat (*Triticum aestivum* L.). Crop residues or growing plants were not present in the furrows during either irrigation. Small trapezoidal, long-throated flumes were installed 18.3-m downslope from the inflow point to measure runoff and to facilitate sampling to estimate sediment and P losses at 5, 15, 45, 75, 135, and 255 min after runoff began. Flow measurements were not sensitive enough to measure the small difference between inflow and outflow rates due to infiltration.

Sediment load was estimated by the 1-L Imhoff cone technique (Sojka et al., 1992). Runoff DRP was determined on a filtered (0.45 μm, within 5 min) sample stabilized with 1 mL of saturated H_3BO_3 per 100 mL sample, while FeO-P_w (iron-oxide impregnated filter paper strip; Sharpley, 1993) and total P (persulfate digestion; American Public Health Association, 1992) were determined on an unfiltered sample. Each runoff water sample contained both the suspended and bed-load sediment being carried by the water flow.

Soil samples (0.03 m depth) were taken from the furrow bottom immediately before each irrigation for bicarbonate-extractable inorganic phosphorus (Fur-P_i) and bicarbonate-extractable organic phosphorus (Fur-P_o, after digestion with persulfate) (Olsen et al., 1954), FeO-P_s (iron-oxide impregnated filter paper strip–extractable soil P), and water-soluble P (water P) (Pote et al., 1996). A single-point phosphorus sorption index (PSI) was also determined on the furrow soil sample patterned after the procedure described by Bache and Williams (1971). Briefly, 1.00 g soil was added to 20 mL of 75 mg P L^{-1} solution in 50-mL centrifuge tubes, shaken end-over-end for 18 h at 25°C, centrifuged, and filtered (0.45 μm)

Table 1. Initial soil characteristics and flow-weighted average runoff concentrations.

		Furrow bottom soil‡						Bulk plot soil§		Average runoff concentrations¶			
Year	Plot treatment†	OC	Lime	Fur-P_i	Fur-P_o	FeO-P_s	Water P	STP_iC	STP_oC	DRP	Total P	FeO-P_w	Sediment
		g kg^{-1}		mg kg^{-1}						mg L^{-1}			g L^{-1}
1998	T1-HW	7.9	187	28.8	3.5	53.5	4.4	48.0	6.1	0.008	2.82	0.268	4.9
1998	T2-HW	9.4	107	37.2	3.9	49.5	11.0	42.2	3.9	0.010	1.78	0.241	3.6
1998	S1-HW	5.9	249	51.2	3.2	49.0	4.7	33.1	9.6	0.008	1.91	0.232	2.2
1998	S2-HW	6.8	252	57.8	2.8	54.0	5.5	71.6	20.7	0.009	1.39	0.174	2.3
1998	T1-Man94	9.8	181	51.9	3.6	57.5	9.6	71.7	13.0	0.024	2.45	0.377	4.4
1998	T2-Man94	11.5	86	60.8	2.5	78.5	21.8	65.8	8.3	0.018	1.33	0.259	1.8
1998	S1-Man94	11.3	245	112.8	12.0	129.0	17.4	152.0	59.0	0.017	1.95	0.539	1.6
1998	S2-Man94	11.8	248	119.4	10.6	140.5	19.3	165.7	41.8	0.041	3.15	0.844	2.7
1998	T1-None	9.2	148	18.3	3.2	36.5	3.2	18.4	2.3	0.009	3.47	0.206	4.3
1998	T2-None	9.5	69	25	3.2	42.0	9.4	12.5	3.6	0.012	0.95	0.218	1.4
1998	S1-Conv	7.5	250	45.1	2.5	52.0	4.0	16.2	3.2	0.009	1.38	0.207	1.0
1998	S2-Conv	5.9	244	24.6	2.1	39.5	1.9	23.8	2.3	0.007	0.56	0.108	0.2
1998	T3-None	7.7	96	10	9.5	32.5	5.0	18.2	2.8	0.012	1.08	0.120	1.7
1998	T4-None	10.4	53	11.9	10.9	50.0	8.1	10.5	3.6	0.018	2.09	0.149	3.6
1998	S1-Man91	11.4	257	58.4	36.4	98.0	13.6	66.8	10.8	0.021	2.90	0.428	1.4
1998	S2-Man91	9.6	223	51.7	21.5	84.0	13.7	112.5	32.5	0.025	3.09	0.451	3.4
1999	T1-HW	8.1	188	38.9	5.6	55.5	7.3	31.8	2.6	0.015	1.29	0.167	2.1
1999	T2-HW	8.6	131	40.5	2.9	60.0	10.3	45.7	2.9	0.023	1.86	0.238	2.4
1999	S1-HW	7.4	246	52.7	5.8	78.0	5.4	64.7	5.1	0.014	1.36	0.253	1.2
1999	S2-HW	6.3	249	59.3	5.0	68.0	6.4	44.6	11.5	0.017	1.92	0.322	1.7
1999	T1-Man94	11.5	179	68.3	13.3	89.5	15.1	51.8	26.1	0.032	1.33	0.304	1.4
1999	T2-Man94	10.6	92	50	5.7	61.5	18.8	55.6	16.3	0.032	1.57	0.234	2.5
1999	S1-Man94	10.2	243	121.2	12.2	123.5	18.5	105.7	41.4	0.033	1.41	0.303	0.9
1999	S2-Man94	8.1	248	119.4	10.0	115.0	17.3	68.3	21.3	0.036	0.95	0.293	0.4
1999	T1-None	8.9	149	17.5	0.4	37.5	2.6	18.9	5.6	0.012	1.18	0.192	1.8
1999	T2-None	9.3	70	20.2	0.4	41.0	7.6	22.8	1.9	0.018	0.98	0.128	0.9
1999	S1-Conv	6.5	252	32	0.4	43.0	2.9	32.9	4.5	0.021	1.61	0.260	1.3
1999	S2-Conv	5.3	243	30.4	0.3	62.0	2.9	23.7	0.8	0.013	0.80	0.210	0.5
1999	T3-None	8.6	89	16.5	0.1	26.0	4.5	16.7	3.6	0.016	2.20	0.169	5.0
1999	T4-None	9.0	45	17.4	0.0	45.5	8.0	20.8	2.8	0.018	1.55	0.209	3.0
1999	S1-Man91	9.3	241	68.4	12.5	99.5	11.4	73.1	1.7	0.043	0.62	0.212	0.6
1999	S2-Man91	10.2	240	125.2	13.3	96.0	19.1	78.4	20.3	0.039	1.86	0.384	1.6

† T, topsoil; S, subsoil; HW, high whey; Man91, manure applied in 1991; Man94, manure applied in 1994; Conv, conventional fertilizer practices; None, control treatment (Robbins et al., 1997).

‡ OC, organic carbon; Fur-P_i, bicarbonate-extractable inorganic phosphorus; Fur-P_o, bicarbonate-extractable organic phosphorus; FeO-P_s, iron-oxide impregnated paper–extractable phosphorus; water P, water-extractable inorganic phosphorus.

§ STP_iC, inorganic phosphorus; STP_oC, organic phosphorus.

¶ DRP, dissolved molybdate-reactive phosphorus; total P, phosphorus concentration after persulfate digestion; FeO-P_w, iron-oxide impregnated paper–extractable phosphorus.

for DRP analysis. The PSI was calculated as the P sorbed by the soil divided by the logarithm of the equilibrium P concentration in solution. In addition, a composite 0.30-m spring soil sample from each plot was analyzed for Olsen-extractable P and inorganic (STP_iC) and organic (STP_oC) P. All P concentrations were determined by the molybdenum-blue method (Murphy and Riley, 1962). Acid equivalent lime (Allison and Moodie, 1965) and organic carbon (OC) (Nelson and Sommers, 1982) were also determined on the furrow soil sample. Runoff data were integrated over time to calculate cumulative P and sediment losses and flow-weighted average P and sediment concentrations for an irrigation, and then subjected to simple linear and stepwise regression analysis (SAS Institute, 1989). Independent variables were added to the regression equation when $p < 0.01$ for the coefficient of partial correlation. The 1998 and 1999 data were combined since initial analysis showed that the relationships among variables were similar in both years. This provided 32 observations for the regression analyses of each comparison.

RESULTS

Soil Phosphorus Tests

The Fur-P_i concentrations ranged from 10 to 125 mg kg^{-1} (Table 1). Soil Olsen P concentrations of 20 to 30 mg kg^{-1} are normally considered adequate for crop production on calcareous soils. The Fur-P_i concentrations were similar to those determined in the 0.3-m samples taken for agronomic diagnostic purposes ($r^2 = 0.67$, $P < 0.05$; data not shown). Inorganic P concentrations in the equilibrium soil solution were between 0.05 and 1.34 mg L^{-1} for this range of soil Olsen P concentrations (Robbins et al., 1999).

The furrow soil P concentrations extracted by the different methods were related. There was a significant relationship between the furrow soil FeO-P_s and Fur-P_i (FeO-P_s = 25.7 + 0.81 × Fur-P_i, $r^2 = 0.84$, $P < 0.05$). The FeO-P_s concentrations ranged between 26 and 140 mg kg^{-1}, while the furrow-soil water P concentrations were between 1.9 and 21.8 mg kg^{-1} (Table 1). Furrow-soil water P was linearly related to both Fur-P_i and FeO-P_s ($r^2 = 0.61$ and 0.58, respectively, $P < 0.05$). Correlations among indices of furrow soil test P concentrations were similar for both 1998 and 1999 (data not shown).

Phosphorus Runoff Relationships

The highest sediment and P concentrations in the runoff were found in the 5-min runoff sample (data not shown). These normally declined exponentially, reaching steady-state after about 135 min, when the runoff DRP concentration approached the inflow concentration. Total P runoff concentration always exceeded inflow concentration and depended on sediment concentration. The DRP loss for an entire irrigation event was between 0.04 and 0.20 kg P ha^{-1} compared with total P losses between 2.8 and 19.3 kg P ha^{-1}. Similarly, FeO-P_w in the runoff varied between 0.37 and 4.16 kg P ha^{-1}. Median total P loss and runoff concentrations per irrigation were 7.3 kg P ha^{-1} and 1.6 mg P L^{-1}, respectively. The median total loss of DRP and FeO-P_w in the runoff was 0.08 kg P ha^{-1} and 1.19 kg P ha^{-1}, respectively. The irrigation-induced soil erosion varied between 0.9 and 17 Mg ha^{-1}. The median runoff sediment concentration was 1.7 g L^{-1}.

Table 2. Simple linear correlation coefficients between average runoff P concentrations and soil P tests for 1998 and 1999 combined.†

Average P runoff	Furrow soil P tests‡			Average P runoff§	
	Fur-P_i	FeO-P_s	Water P	Total P	DRP
	r				
DRP	0.69	0.74	0.74	0.04	1.00
FeO-P_w¶	0.68	0.77	0.59	0.56	0.52
Total P	0.08	0.15	0.12	1.00	0.04

† $r > 0.35$ is significant at 5% probability, $n = 32$.
‡ Fur-P_i, bicarbonate-extractable inorganic phosphorus; FeO-P_s, iron-oxide impregnated paper–extractable phosphorus; water P, water-extractable inorganic phosphorus.
§ Total P, phosphorus concentration after persulfate digestion; DRP, dissolved molybdate-reactive phosphorus.
¶ Iron-oxide impregnated paper–extractable phosphorus from unfiltered runoff water.

Average runoff DRP concentrations were relatively low in this study (0.007–0.043 mg P L^{-1}) because the short furrow length and high inflow rate produced a relatively short contact time in the furrow (~0.58 min). Runoff DRP was significantly related to average runoff FeO-P_w but not to total P (Table 2). Average FeO-P_w concentration was related to total P (Table 2) because the iron-oxide strip extracts P released by the sediment during the extraction as well as the initial soluble P. Median FeO-P_w concentration was 13-fold and 0.15-fold that for DRP and total P concentration, respectively.

All furrow soil P tests were linearly related to the average runoff DRP concentration with the highest correlation for furrow-soil water P (Fig. 1). Runoff DRP concentration was not related to sediment concentration ($r = -0.25$). Including sediment concentration with any furrow soil P test did not improve the regression relationships nor did evaluating other independent variables (furrow-soil organic carbon [OC] or lime, Table 1) via stepwise regression improve the relationship over that between furrow-soil water P and average runoff DRP concentration.

The best relationship between furrow soil P tests and average runoff FeO-P_w concentration was with the furrow soil FeO-P_s, followed by Fur-P_i and water P (Fig. 1). In all three comparisons there was a general increase in FeO-P_w concentration as the soil test P concentration increased. Their coefficients of simple determination (r^2) were similar to those found for DRP. Performing a stepwise regression with the average FeO-P_w concentration as the dependent variable, and the furrow soil P tests and average runoff sediment as independent variables, selected the average runoff sediment concentration and furrow FeO-P_s in this equation:

$$\text{Average FeO-}P_w = -0.096 + 0.040(\text{sediment}) + 0.0042(\text{FeO-}P_s),\ R^2 = 0.69\ (P < 0.05)$$

There was no significant relationship between average runoff total P concentration and any furrow soil P test for either year or combined years (Table 2). However, simple regression analysis showed that the sedi-

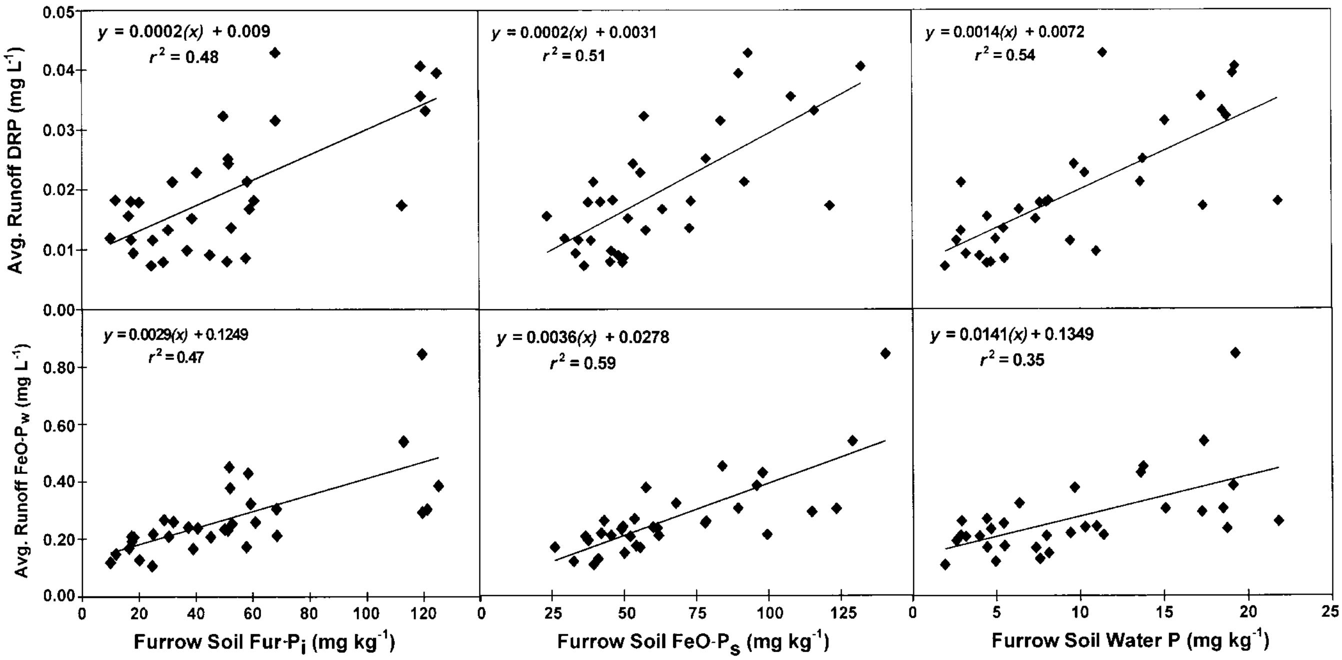

Fig. 1. Linear relationships between average runoff dissolved reactive phosphorus (DRP) and iron-oxide impregnated paper–extractable phosphorus from unfiltered runoff water (FeO-P$_w$) concentrations, and furrow soil P tests (r^2 > 0.12 significant at 5% probability).

ment and total P concentration relationship was significant (Table 3). Stepwise regression was performed with the average total P concentration as the dependent variable, and the furrow soil P tests and average runoff sediment concentration as independent variables. Average runoff sediment concentration was the first variable selected, followed by soil lime and furrow Fur-P$_o$ concentration (Table 3). Partial coefficients for each selected independent variable were highly significant ($P <$ 0.01). Substituting other furrow soil P tests for the furrow Fur-P$_o$ concentration did not improve the relationship.

The relationship between average runoff total P and furrow soil tests was further evaluated by separating the manured plots from the nonmanured plots and the topsoil from the subsoil plots. In both data sets, the best simple regression was with average sediment concentration (Table 3). Stepwise regression of the manured plots selected average sediment concentration, furrow Fur-P$_o$, and FeO-P$_s$ in the final equation. For the nonmanured plots, average sediment concentration and furrow-soil lime concentration were selected (Table 3). For either the topsoil or subsoil plots, the average sediment concentration was initially selected. Fur-P$_o$ was further selected for the subsoil plots but no additional selection was made for the topsoil plots. The selection of Fur-P$_o$ was probably influenced by past manure applications, particularly on the subsoil plots, since only the manured plots contained appreciable amounts of $NaHCO_3$–extractable organic P (Table 1). Lime was probably selected because it was positively correlated ($P < 0.05$) to a number of variables including average runoff sediment concentration, sediment's total P concentration, FeO-P$_s$, and Fur-P$_i$ (data not shown). Accumulated sediment losses were also smaller on the high lime plots (Bjorneberg et al., 1999b).

DISCUSSION AND CONCLUSIONS

The average runoff DRP concentration increased as soil P availability increased. This relationship was similar for the Olsen P extracted from the bulk plot soil ($\hat{y} = 0.0115 + 0.0002x$) and for the soil in the bottom of the furrow ($\hat{y} = 0.009 + 0.0002x$; Fig. 1). This indicates that a soil sample normally used for plant nutritional diagnostic purposes may also be used to indicate soluble P losses, provided the soil and P source were previously mixed by tillage operations. Soluble P losses in surface irrigation runoff will be reduced if the P-enriched soil is physically separated from the flowing water in the

Table 3. Simple and stepwise regression results between average runoff total P concentration (department variable) and average runoff sediment concentration and furrow soil parameters (1998 and 1999 combined).†

All plots (n = 32)	
$Y = 0.833 + 0.413$ (sediment)	$r^2 = 0.52$
$Y = -0.184 + 0.511$ (sediment) + 0.031 (lime) + 0.037 (Fur-P$_o$)‡	$R^2 = 0.77$
Manured plots (n = 12)	
$Y = 0.971 + 0.482$ (sediment)	$r^2 = 0.46$
$Y = -1.54 + 0.712$ (sediment) + 0.051 (Fur-P$_o$) + 0.015 (FeO-P$_s$)§	$R^2 = 0.92$
Nonmanured plots (n = 20)	
$Y = 0.664 + 0.417$ (sediment)	$r^2 = 0.70$
$Y = 0.089 + 0.479$ (sediment) + 0.026 (lime)	$R^2 = 0.75$
Topsoil plots (n = 16)	
$Y = 0.438 + 0.465$ (sediment)	$r^2 = 0.75$
Subsoil plots (n = 16)	
$Y = 0.565 + 0.774$ (sediment)	$r^2 = 0.69$
$Y = 0.369 + 0.673$ (sediment) + 0.036 (Fur-P$_o$)	$R^2 = 0.83$

† All r^2 and R^2 significant at 1% probability level.
‡ Fur-P$_o$, bicarbonate-extractable organic phosphorus from furrow soil.
§ FeO-P$_s$, iron-oxide impregnated paper–extractable phosphorus from furrow soil.

furrow. This may be accomplished by banding or deep placement of P below the soil's surface by tillage operations. In addition, only the surface layer of soil in contact with the flowing water would need to be sampled to predict soluble P losses.

Runoff studies also show that the soluble P concentration is related to the P saturation of the sorption complex (Pote et al., 1999; Tunney et al., 1997). Phosphorus saturation is determined from the ratio of P on the sorption complex divided by the sorption maximum usually determined from P adsorption isotherms. The P on the sorption complex can be estimated by isotopic exchange or by anion exchange resins. Another approach used for acid soils is to calculate the phosphorus saturation from oxalate-extractable P, Fe, and Al (Van der Zee et al., 1990). This approach does not work satisfactorily where the sorption complex consists primarily of lime materials as in calcareous soils. A phosphorus sorption index (PSI) may also be estimated from a single-point P sorption procedure estimating sorption capacity (Bache and Williams, 1971; Mozaffari and Sims, 1994). Pote et al. (1999) extended this concept to show that the runoff soluble P concentration from three acid soils was related to the ratio of the soil test P concentration divided by the PSI adjusted to the maximum sorption for acid soils. We explored this approach but the PSI was not adjusted to maximum sorption since a suitable relationship between PSI and maximum sorption is not known for calcareous soils. The ratio between either Fur-P_i or FeO-P_s and PSI was significantly related to the average runoff DRP concentration in this study (Fig. 2). However, there was only a slight improvement in the regression relationships when compared with the relationships using only the soil test P concentrations (Fig. 1). The PSI ranged between 170 and 315 and was linearly related to the lime concentration (PSI = 162 + 4.46 × lime, r^2 = 0.71, $P < 0.5$). Adding either Fur-P_i or FeO-P_s to this relationship as an independent variable increased R^2 to more than 0.86. The partial coefficients for Fur-P_i and FeO-P_s both are negative, indicating that as soil test P concentration increases the PSI decreases for a given soil, which should be expected since more P is initially on the available sorption sites.

The FeO-P_w concentration in the runoff is an estimate of the bioavailable P (Sharpley, 1993). In this study, the runoff FeO-P_w concentration was best estimated by including the furrow soil FeO-P_s concentration and the average runoff sediment concentration ($R^2 = 0.69$, $P < 0.05$). The inclusion of sediment occurs because the iron-oxide impregnated paper strip procedure extracts P released by the sediment over the 18-h extraction period as well as the initial soluble P. Fur-P_i might be used in place of FeO-P_s to estimate bioavailable P losses in runoff since the FeO-P_s concentration was closely related to the Fur-P_i ($r^2 = 0.84$). However, replacing FeO-P_s with Fur-P_i reduced the R^2 to 0.57, compared with 0.69 when using FeO-P_s.

The total P concentration of the runoff sediment (i.e., [runoff total P minus DRP]/runoff sediment concentration, mg kg^{-1}) was weakly related to the P (inorganic and organic) extracted by the Olsen method (sediment total P = 640 + 6.38 × Olsen P; $r^2 = 0.23$, $P < 0.05$). This relationship improved slightly when the total P concentration of the furrow soil (data not shown) was regressed against total Olsen P ($r^2 = 0.45$). A relationship between the total P concentration of the eroded sediment and furrow soil was not significant ($r^2 = 0.12$). Similar to the runoff total P concentration, the eroded sediment's total P concentration was also weakly related to lime concentration ($r^2 = 0.37$).

Total P losses were not related to any measure of soil P availability in this study. This probably occurred because the fraction of soil P extracted by any of the soil test P methods was relatively small (<10%) when compared with the soil's total P concentration. In addition, the relationship of soil test P concentration and runoff total P loss does not consider the amount of suspended sediment (g L^{-1}). The inclusion of sediment concentration in the regression equations indicates that predicting total P loss in surface irrigation runoff will not be successful until soil erosion can be satisfactorily predicted. Carter et al. (1974) also reported that soil erosion or runoff control was necessary to limit P losses from surface-irrigated fields. It should be pointed out that even the lowest Fur-P_i concentration (10.0 mg kg^{-1})

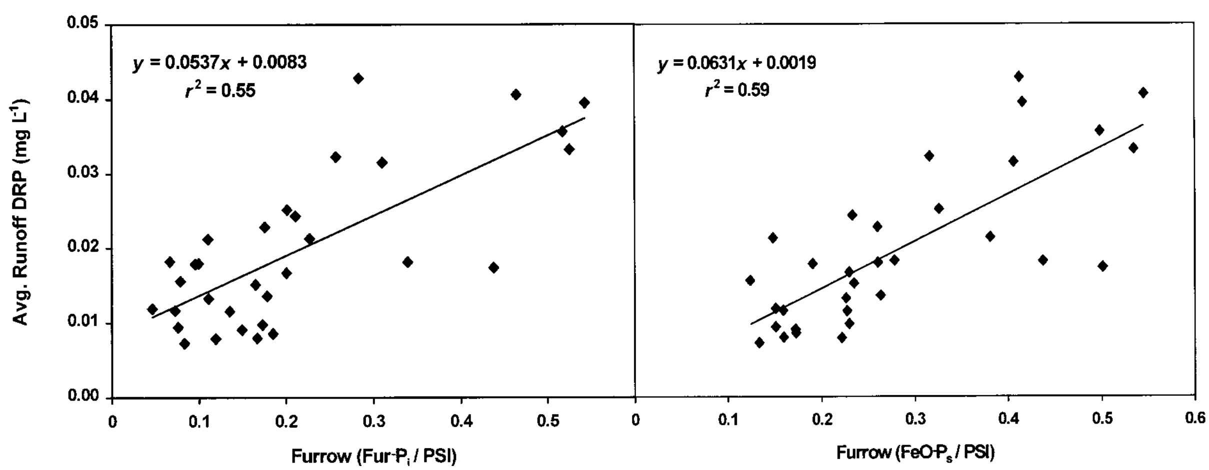

Fig. 2. Linear relationships between average runoff dissolved reactive phosphorus (DRP) concentrations and ratio of either bicarbonate-extractable inorganic phosphorus from furrow soil (Fur-P_i) or iron-oxide impregnated paper–extractable phosphorus from furrow soil (FeO-P_s) divided by phosphorus sorption index (PSI) ($r^2 > 0.12$ significant at 5% probability).

had an average runoff total P concentration of 1.08 mg L^{-1} substantially exceeding the limit of 0.1 mg L^{-1} suggested by the USEPA for water flowing to streams and rivers (USEPA, 1986).

Our average runoff DRP concentrations were lower than those reported in other furrow irrigation runoff studies (Berg and Carter, 1980; Carter et al., 1974) and in rainfall simulation studies (Pote et al., 1996; Sharpley et al., 2000; Tunney et al., 1997). Runoff DRP concentrations were as high as 0.167 mg L^{-1} but averaged near 0.080 mg L^{-1} at the 5-min sampling (data not shown). Since DRP concentration generally increases as the furrow irrigation water moves across a field and decreases with time (Bjorneberg et al., 1999a), runoff DRP concentration strongly depends on furrow length and flow rate.

The relationships between either average runoff DRP or FeO-P_w concentration and soil test P concentration appears to be linear over the range of soil test P concentrations in this study. If there is a soil P concentration for this soil type above which the runoff P concentration rapidly accelerates it must be at a greater soil test P concentration than present in our study. This slope change would indicate that the P sorption complex was saturated. The soil test P concentration at this point would probably be significantly greater than the normal agronomic requirement.

Previously established treatment characteristics in our data set probably affected our results. This was partially shown by the selection of Fur-P_o, the organic P extracted by the Olsen P method, in the regression equation related to average runoff total P concentration (Table 3). Because of past manuring some of this study's treatments had extractable organic P concentrations above those normally found for nonmanured soils (Table 1). Without these treatments, Fur-P_o may not have been selected. Unfortunately, organic P was not determined on the filtered runoff sample to determine if soluble organic P losses were significant. Likewise, lime was probably selected because the subsoil plots, with higher lime concentrations, also had higher soil test P concentrations than the topsoil plots. Additional studies need to be conducted on larger fields and across a wider range of field conditions to confirm the soil test P–runoff P relationships and to identify primary source areas in larger fields and scaling effects.

Runoff DRP and FeO-P_w concentrations were related to furrow soil P availabilities. The relationships decreased in order of water P $>$ FeO-P_s $>$ Fur-P_i for DRP, and FeO-P_s $>$ Fur-P_i $>$ water P for FeO-P_w, respectively. Total P losses were primarily related to sediment concentrations. Soil lime concentrations and Fur-P_o also appeared to be important components affecting total P loss. Average runoff total P concentrations exceeded water quality standards even at the lowest soil test P concentration.

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Factors Affecting Alkalinity Generation by Successive Alkalinity-Producing Systems: Regression Analysis

C. R. Jage, C. E. Zipper,* and R. Noble

ABSTRACT

Use of successive alkalinity-producing systems (SAPS) for treatment of acidic mine drainage (AMD) has grown in recent years. However, inconsistent performance has hampered widespread acceptance of this technology. This research was conducted to determine the influence of system design and influent AMD chemistry on net alkalinity generation by SAPS. Monthly observations were obtained from eight SAPS cells in southern West Virginia and southwestern Virginia. Analysis of these data revealed strong, positive correlations between net alkalinity generation and three variables: the natural log of limestone residence time, influent dissolved Fe concentration, and influent non-Mn acidity. A statistical model was constructed to describe SAPS performance. Subsequent analysis of data obtained from five systems in western Pennsylvania (calibration data set) was used to reevaluate the model form, and the statistical model was adjusted using the combined data sets. Limestone residence time exhibited a strong, positive logarithmic correlation with net alkalinity generation, indicating net alkalinity generation occurs most rapidly within the first few hours of AMD–limestone contact and additional residence time yields diminishing gains in treatment. Influent Fe and non-Mn acidity concentrations both show strong positive linear relationships with net alkalinity generation, reflecting the increased solubility of limestone under acidic conditions. These relationships were present in the original and the calibration data sets, separately, and in the statistical model derived from the combined data set. In the combined data set, these three factors accounted for 68% of the variability in SAPS systems performance.

Acidic mine drainage is an environmental pollutant of concern in mining areas throughout the world, including the coal mining regions of the Eastern USA (Herlihy et al., 1990). Acidic mine drainage occurs as a result of oxidation of sulfidic minerals associated with coal deposits when they are exposed to O_2 and water during and after mining. Iron pyrite (FeS_2) is responsible for producing the majority of AMD in coal-mining areas (Rose and Cravotta, 1998).

The process is initiated with the oxidation of pyrite in the presence of water and the consequent release of Fe^{2+}, SO_4^{2-}, and acidity. The resulting drainage can be highly acidic and low in pH, and contain elevated concentrations of SO_4^{2-}, Mn, Fe, and other acid-soluble metals. When AMD reaches a receiving stream, it often is toxic to aquatic life and can threaten domestic drinking water supplies (Manyin et al., 1997). Drainage toxicity is affected by dissolved metal concentrations and pH (Earle and Callaghan, 1998). Kleinmann (1989) estimated that, in the United States alone, more than 20 000 km of streams and rivers and more than 72 000 ha of lakes and reservoirs have been adversely affected by AMD.

Acidic Mine Drainage Treatment

Current AMD treatment methods can be divided into two categories: active and passive. Active treatment involves the addition of caustic chemicals such as NaOH or CaO, which raise pH and cause acid-soluble metals to form insoluble complexes and precipitate (Skousen et al., 1998). Active treatment processes are effective but can be expensive due to the need to construct and maintain a treatment facility, and to purchase chemical reagent. Active treatment can also increase the salinity of the receiving stream, which may harm sensitive organisms (Campbell, 1990). Such treatment also produces wet sludges that must be removed periodically and can be costly to dispose of. Active treatment also requires that caustic chemicals be stored on site, creating a potential liability for the operating firm and the stream environment.

Passive treatment systems rely on natural chemical and biological processes to renovate AMD. Aerobic-wetland treatment was one of the first passive designs put into wide use. Aerobic wetlands are constructed as shallow depressions with composted organic-matter substrates planted with cattails (*Typha* spp.) (Skousen et al., 1998; Hedin et al., 1994a). These systems are designed to aerate mine waters flowing among the planted vegetation, thus allowing for Fe^{2+} oxidation and its subsequent deposition as FeOOH. These systems generally precipitate Fe while having little effect on Mn and, in many

C.R. Jage, Regional Land Trust Representative, New Jersey Conservation Foundation, Bamboo Brook, 170 Longview Road, Far Hills, NJ 07931. C.E. Zipper, Dep. of Crop and Soil Environmental Sciences, and R. Noble, Dep. of Statistics, Virginia Polytechnic Institute and State Univ., Blacksburg VA 24061. Research sponsor: Powell River Project, Virginia Polytechnic Institute and State Univ., Blacksburg, VA 24061. Received 22 May 2000. *Corresponding author (czip@vt.edu).

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Abbreviations: AMD, acidic mine drainage; ALD, anoxic limestone drain; SAPS, successive alkalinity-producing systems; t_r, residence time in limestone layer (hours).